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CLOSED 1,001" TESTS OF THE NASA SAPPHIRE PHASE STABILIZER

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Abstract

We have developed a cryogenic Sapphire Phase Stabilizer (S1'S) to meet microwave oscillator phase noise requirements. The S}'S employs a high Q, X-band sapphire dielectric "whispering gallery" mock resonator as a discriminator to stabilize a quartz crystal oscillator, At an untuned frequency of 7.9449 GHz with a loaded Q of 6 million we previously reported an "open loop" discriminator noise floor (referred to 100 MHz) of approximate.ly $S_\phi(f) = -110$ dB/f^3(/Hz) for offset frequencies from f=- 11 Iz 10 f=- 1 kHz.

Precise tuning of the sapphire resonant frequency now allows implementation of simplified control loops together with suppressed-carrier phase sensing circuitry,. These improvements make. possible an ultra-low noise demonstration of closed-loop S1'S performance. 1 from 1 117. to 1kHz a comparison of the S}'S with a quartz crystal reference oscil later of the highest quality showed only the noise of the reference oscillator. To our knowledge these, results represent the lowest phase noise in a closed loop or active sapphire oscillator [o date at temperatures achievable with liquid nitrogen (77K or higher).

Introduction

The SPS is based On a novel technology consisting of a Cooled sapphire "whispering gallery" mock X-band resonator operating in the temperature range from 70 Kelvin to 300 Kelvin - value.s achievable by means of radiative and thermoelectric cooling.

Sapphire, oscillator technology is presently under development in a number of laboratories, with experimental results for designs at 300K[1,2,3], 77K[1,3,51, 35K[6], and liquid helium temperature[7,8,9] being reported. Oscillator configurations include discriminators, active oscillators, and stabilized local oscil laters (STALO) with dc or ac (Pound) frequency sensing. Suppressed carrier techniques have been applied 10 active (bridge) and passive (STAI,()) configurations.

The S}% employs a sapphire resonator operating at 80 Kelvin in a suppressed-carrier STALO configuration.

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We previously reported an open loop measurement of the phase noise. of a quartz oscillator of the highest quality, with a noise floor reduced by 10 to 45 dB for offset frequencies from 1 Hz 10 1000 Hz[1]. By accurately tuning the sapphire resonator, and with simplified circuitry thus allowed, we are now able. to make a similar closed loop comparison.

While the previous tests used an untuned sapphire element, our system is designed to operate critically coupled at 8.1000 GHz with a loaded Q of 15 million at 77 Kelvin. Advantages of this system include a simplified electronic configuration resulting in reduced phase noise. A 3-stage methodology has been (ic.vc.lope.ci to provide the accurate. frequency tuning the S}'S system requires.

Resonator Tuning

The sapphire "whispering gallery" mode resonator frequency can be tuned in three stages, The first stage of tuning is reduction of the physical size of the. sapphire resonator wheel hy machining down the outer diameter and thickness. The $WGH_{10,0,0}$ mode used in our resonator confines ten azimuthal cycles within the. sapphire wheel. Reduction of the wheel's dimensions simply reduces the. available path length for the 10 cycle.s thereby increasing, the resonant frequency. The goal is to reduce the sapphire, wheel such that ii's natural resonant frequency for the WGH 110,,0 mode at 77K is just above 8.1000 GHz. The remaining two tuning methods can then be used to lower the resonant frequency to 8.1000 GHz. The machining process was done in steps so as not to overshoot our capability to fine. tune the resonant frequency. Figure 1 shows the resonant frequency of the resonator as predicted and as measured for each iteration of machining. A simple model was used 10 choose the reduction in each of the sapphire's dimensions and predict the new resonant frequency.

The second tuning method reduces the rc.senator's operational frequency by suspending a sapphire disk above. the. rc.senator wheel as in Figure 2. The additional dielectric material present in the resonant fields decreases the resonant frequency. Mechanical tuning with the sapphire disk used in our experiment reduced the resonant frequency up to ≈30 MHz (if positioned directly on top of the resonator). The sapphire tuning disk is attached to a micrometer drive so mechanical tuning earl be done ~f'hilt. the resonator is operating. This technique provides a large tuning range, but is susceptible, and very

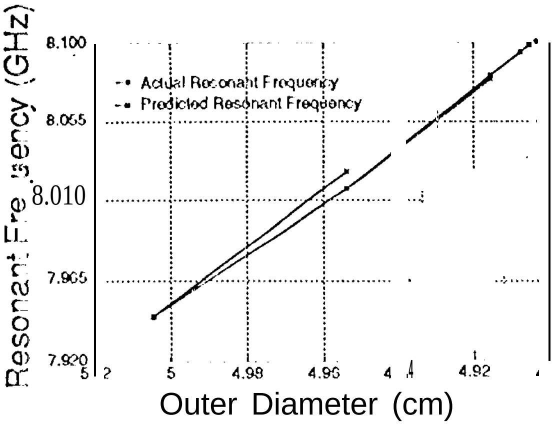

Figure 1. Resonant Frequency as a Function of Resonator Outer Diameter

sensitive, to vibration. The tuning disk must be held extremely rigidly so as 10 remain parallel to the resonator wheel. The resonator's frequency stability is determined by the tuning disk's mechanical /vibrational stability [10].

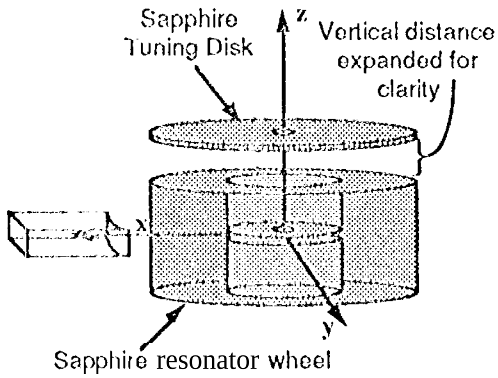

Figure 2. Mechanical Tuning with disk above, resonator wheel

The third tuning method provides fine tuning of the resonator's frequency by the.rlnal]y controlling the resonator. The thermal expansion of the sapphire reduces the resonant frequency. The sapphire wheel as pictured in Figure 2 sits on a copper post wrapped with a heater wire. The copper post sits in a metal cylinder of lesser thermal conductivity. This cylinder is heat sunk to the outer copper resonator containment can which is cooled by liquid nitrogen. in this fashion we c an coo] the sapphire to liquid ni rogen temperature or warm it to a few Kelvin above 77K. Figure 3 shows an example of thermally tuning resonant frequency. Resonant frequency and resonator temperature are shown as a function of the heater power applied in the resonator.

Figure 3 shows approximately 300 kHz of tuning capability. Therefore the coarse tuning methods must bring the resonant frequency to within several hundred k] Iz. For the heater assembly currently installed in the resonator we calculate a maximum operational heater

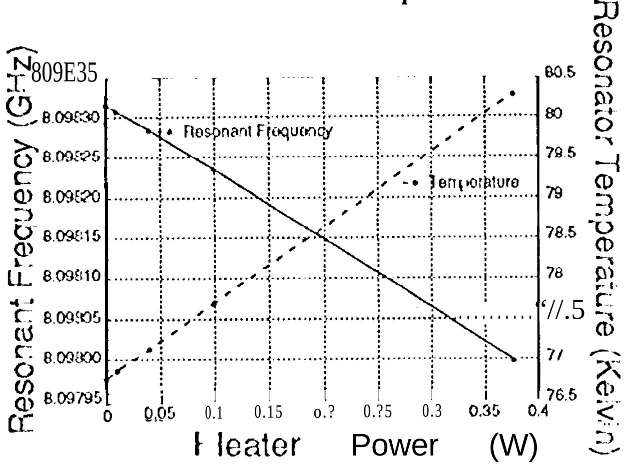

Figure 3. Resonator Response to Heater Power

wire current as seen in Figure 4. At maximum heater power the resonator would operate at ≈86K with resonant frequency reduced by ≈] h4 Hz.

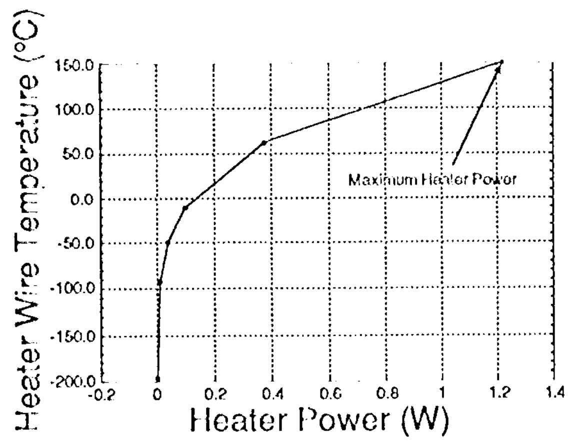

Figure 4. Radiation Limit of Heater Wire Temperature vs. Heater Power

For reduced vibrational sensitivity and there.fore optimum phase noise performance, we opted to mac.hint the sapphire resonator wheel to within 500 kHz above 8.100 GHz so that thermal tuning brings the resonator 10 the operational frequency.

Coupling and Quality Factor

Operation at the design frequency is essential for optimization of the electronic configuration, but mom critical to the performance as a low noise stabilized oscillator arc the characteristics of the discriminator. The discriminating power is determined by the high Q cavity operating in a critically coupled condition. Critical coupling with a loaded Q of 15 million requires both a sapphire intrinsic Q and resonator coupling Q of 30 million, Our design uses waveguide coupling ports operating below natural cutoff due to Teflon dielectric loading of the waveguide. The length of the Teflon insert determines the coupling to the sapphire resonator wheel. Loading the entire waveguide port produces an overcoupled condition and therefore a low coupling Q. Loading a portion of the waveguide port can provide us the, critical coupling we desire, although other more subtle aspects of the rf transmission system also effect the coupling Q,

The sapphire resonator's intrinsic Q is expected to be approximately 30 million at 77K, but the actual intrinsic Q is affected by impurities, resonator geometry and alignment, and temperature. We have operated the sapphire resonator very near critical coupling at loaded Q's around 12 million. The coupling and quality factors are determined from simple measurements. The time constant required for a 3 to 1 decay in signal voltage amplitude (τ_{31}) is measured by pulsing the X-band drive signal and monitoring the decaying reflected signal from the resonator. The maximum voltage amplitudes of the reflected resonator input and output (V_{in}, V_{out}) are also measured. Given the resonant frequency (f) the following calculations are performed to determine the measured (loaded), intrinsic and coupling time constants (τ_m, τ_i, τ_c) and the respective quality factors (Q_m, Q_i, Q_c).

$$\tau_m = \frac{\tau_{31}}{2 \cdot \ln(3)} \tag{1}$$

$$\tau_i = \tau_m \cdot \left[1 + \frac{1}{\left(2 \cdot \frac{V_{out}}{V_{in}} - 1 \right)} \right] \tag{2}$$

$$\tau_c = \tau_i \cdot \left(2 \cdot \frac{V_{out}}{V_{in}} - 1 \right) \tag{3}$$

$$Q_m = 2 \cdot \pi \cdot f \cdot \tau_m \tag{4}$$

$$Q_i = 2 \cdot \pi \cdot f \cdot \tau_i \tag{5}$$

$$Q_c = 2 \cdot \pi \cdot f \cdot \tau_c \tag{6}$$

These parameters are regularly monitored to evaluate the various systematic changes made to satisfy design and performance goals.

Electronics

The high Q resonator is implemented in the Sapphire Phase Stabilizer system sketched in Figure 5 which includes suppressed carrier feedback circuitry[11]. The SPS circuitry is designed for optimum sensitivity and phase noise performance at critical coupling. When under or overcoupled the signal returned from the resonator is not a small (nominally zero) signal. Therefore implementation of a rf feedback amplifier requires pre-processing of the resonator return signal. Attenuation and filtering successfully artificially produce the small signal feedback, but some of the suppressed carrier sensitivity is sacrificed.

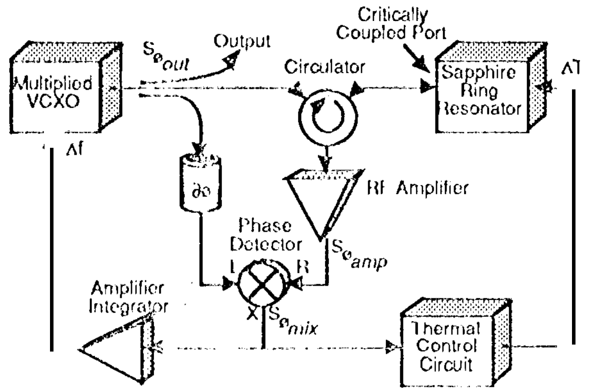

Figure 5. Block Diagram of Sapphire Phase Stabilizer (SPS)

Phase Noise Measurements

Tests of the SPS were made at 80 Kelvin using the circuit shown in Fig. 5 without the rf feedback amplifier and with the circulator replaced by a 3 dB hybrid coupler. The hybrid allows lower noise operation at the expense of signal strength. The under coupled resonator with a loaded Q of approximately 8 million dictated initial testing without suppressed carrier implementation. The current tuning step gave an operational frequency of 8.0995 6117J which forced use of a frequency synthesizer during phase noise measurements. Figure 6 shows the SPS phase noise (referred to 100 MHz) measured at 100 MHz and at X-band. The phase noise measured at 100 MHz was limited by the HP3325A synthesizer used to generate the measurement system's local oscillator frequency. Measurement of the phase noise at X-band, however, reduced the system sensitivity to the synthesizer noise, thereby lowering the measurement system noise floor. Unfortunately the X-band measurement is also limited by the measurement system noise floor, so the actual phase noise performance of the SPS without the rf feedback amplifier is not known at this time.

Also displayed in Figure 6 is the phase noise of the Vectron VCXO used in the SPS. This phase noise was measured by using the resonator as an open loop discriminator. The open loop discriminator noise floor was not measured at that time, but is expected to be similar to previous measurements [1].

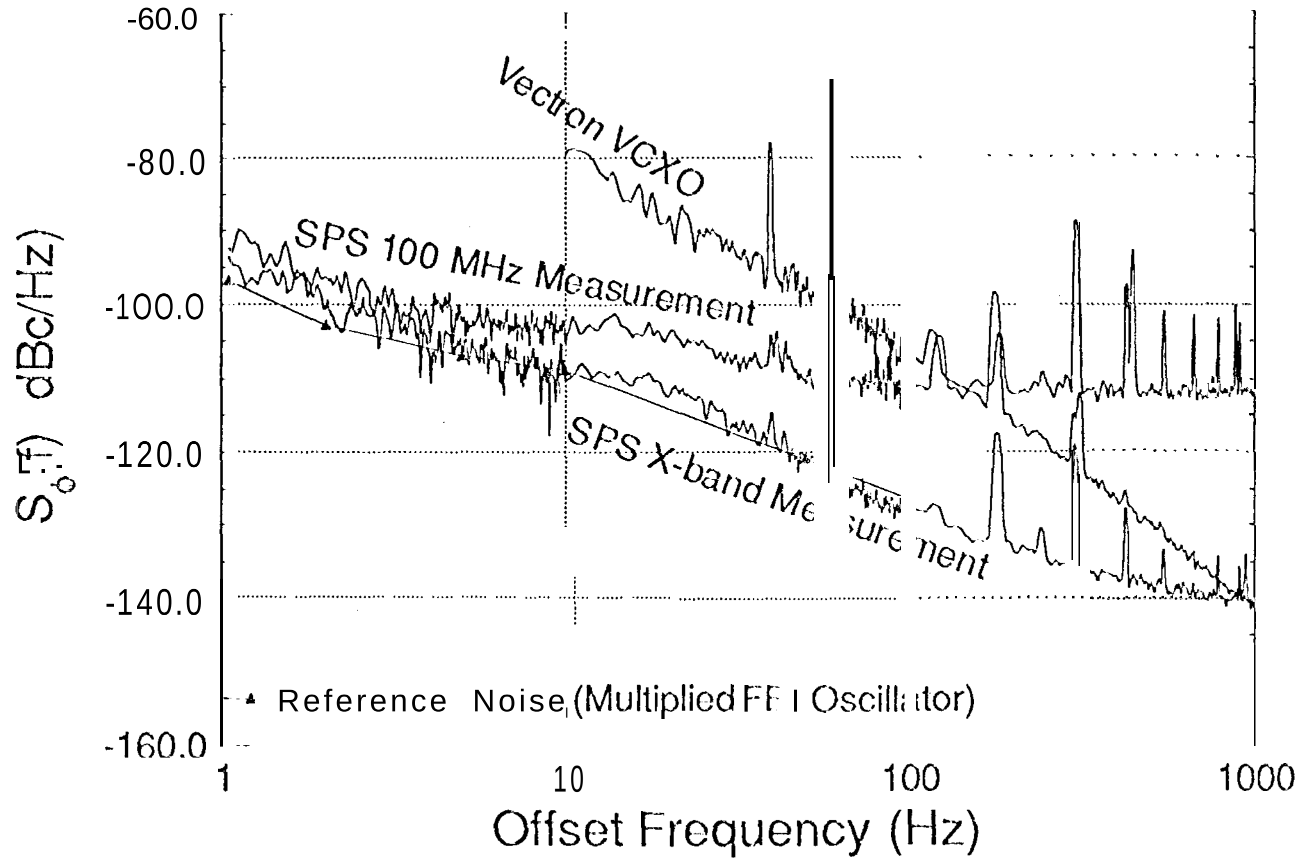

Figure 6. Closed Loop S1'S Phase Noise referred to 100 MHz

Conclusion

A closed-loop dmonstr'alien of Sapphire Phase Stabilizer performance has been made. possible by accurate tuning of the sapphire resonator. In this demonstration, the SPS output frequency was compared with an ultra-low noise quartz crystal reference oscillator, with the results showing only the phase noise of the reference oscillator. This represents the lowest phase, noise measurement for a sapphire oscillator operating at temperatures achievable by cooling with liquid nitrogen.

Actual phase noise. for the S1'S was not measure.{i in this test, only determined to be less than that of the reference osci 1 lator. A second sapphire resonator is presently being tuned 10 allow this performance to be accuratel y determined.

Acknowledgments

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